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Letter to the Editor

Effects of granulation on the visibility of solar oscillations

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ABSTRACT

Context. The interaction of solar oscillations with near surface convection is poorly understood. These interactions are likely the cause of several problems in helio- and astero-seismology, including the so-called surface effect and apparently unphysical travel time shifts as a function of center to limb distance. There is thus a clear need for further theoretical understanding and observational tests.
Aims. The aim is to determine how the observed modes are affected by the convection.
Methods. I use HMI velocity and intensity images to construct k-ω diagrams showing how the oscillation amplitude and phase depend on the local granulation intensity.
Results. There is a clear and significant dependence of the observed properties of the oscillations on the local convection state.

Key words. Sun: granulation - Sun: oscillations

1. Introduction

The effect of convection on wave propagation is a complex issue. With no clear separation of scales in time or space, simple approaches do not work well. This is particularly unfortunate as there are observed effects for the Sun and other stars which are suspected of being due to such effects. While attempts at more complete treatments have been made (e.g. Stix & Zhugzhda 2004; Hanasoge et al. 2013; Bhattacharya et al. 2015), the details are still far from understood.

One example is the so-called surface effect, which has been known for a long time (e.g. Christensen-Dalsgaard et al. 1988) and which manifests itself as a difference between the theoretical and observed mode frequencies and has properties suggesting a near surface origin. For recent discussions of this see Piau et al. (2014) and Ball & Gizon (2014).

Another troubling effect is a time shift observed in time-distance helioseismology with an apparently unphysical dependence on the observable and a strong center-to-limb dependence (see, e.g. Zhao et al. 2012). An attempt to explain this was made by Baldner & Schou (2012), who noticed that eigenfunctions in hydrodynamic simulations exhibit strong phase variations with depth and were able to roughly explain this, as well as the center-to-limb effects, using a crude theoretical model incorporating some of the properties of the convection.

Here I address the latter of these two issues by investigating how the appearance of the oscillations depends on whether one observes them in the middle of granules or in intergranular lanes.

2. Method

While the interaction of waves with convection is complex, it is probably reasonable to try a simple model and start by considering a horizontally uniform and initially vertically propagating wave in a Cartesian box. The two largest contributors to the distortion of the observed wave are likely the local thermodynamic state (i.e. sound speed, as given by the temperature and thus intensity) and the vertical flow, which are highly correlated. Here I use the intensity, as it is easily measured and is less affected by the modes than the Doppler velocity. It is probably also reasonable to linearize the variations, that is to assume that the observed velocity varies linearly with intensity. Of course, the effect is not expected to be a real multiplicative factor, nor independent of frequency, so is best described in the Fourier domain:

$$\widetilde{V}(\omega, I') = \widetilde{V}_0(\omega)(1 + \alpha(\omega)I') \tag{1}$$

where $\widetilde{\ }$ indicates Fourier transform, V is the line-of-sight velocity, V_0 the unperturbed velocity, I' is the intensity minus the mean (over time and space), ω the frequency, and α a complex factor to be determined.

To measure the effect I use data cubes from the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) of Doppler velocity (V) and computed continuum intensity (I), tracked by Langfellner et al. (2014) at the rate of Snodgrass (1984) evaluated at the center of each cube. These have 512 by 512 pixels of size 0.0005 radians by 0.0005 radians ($\approx$ 348 km by 348 km) and 1920 points spaced by 45s in time, for a total cube size of $\approx$ 180 Mm by 180 Mm by 24 hours. For the present study cubes centered on latitudes 0°, ±20°, ±40° and ±60° crossing the central meridian near the center of the time interval are used. A few missing frames each day are filled by interpolating the adjacent images linearly. Also, for ease of interpretation, $I' = I/\overline{I} - 1$, where $\overline{I}$ is the mean (over time and space) of I, is used.

Each frame of the cubes is subdivided into 4x4 pixel areas and two quantities are calculated: $\overline{V}$, which is the average of V, and $\overline{S}$ which is the slope from a linear fit of V versus I. Rather than oversampling, the resulting images have 1/4 as many pixels in each direction.

In reality α might depend on the horizontal wavenumber of the wave, so instead of simply averaging horizontally, the resulting cubes are circularly apodized between 0.85 and 0.95 of their half width with a raised cosine and Fourier transforms $\widetilde{\overline{V}}$ and $\widetilde{\overline{S}}$

are calculated from $\overline{V}$ and $\overline{S}$. From these, α is obtained from the ratio of the cross spectra and power spectra as:

$$\alpha(k,\omega) = \frac{\langle \widetilde{S}(k_x,k_y,\omega,i)\widetilde{V}(k_x,k_y,\omega,i)^*\rangle}{\langle \widetilde{V}(k_x,k_y,\omega,i)\widetilde{V}(k_x,k_y,\omega,i)^*\rangle}, \quad (2)$$

where $\langle\rangle$ denotes averaging over azimuth ϕ and time (indexed by the cube number i) [1] , $k_x = k\cos\phi$, $k_y = k\sin\phi$, $k = l/R_\odot$ is the (horizontal) wavenumber, l the spherical harmonic degree, * indicates complex conjugation, and $R_\odot$ the solar radius. For the results shown here the time averaging was over 30 one day cubes starting on 2010 June 1.

When determining $\overline{V}$ and $\overline{S}$ it is effectively assumed that the horizontal wavelength is long compared to 4 pixels, which may lead to some degradation of the results near the spatial Nyquist frequency of the $\overline{V}$ and $\overline{S}$ maps. However, far from the Nyquist frequency this should not be a problem. Similarly, the use of $\overline{V}$ as an estimate of V_0 should be a good approximation as the term $\alpha(\omega)I'$ in Eq. 1 is small.

3. Results

Fig. 1 shows that there is a strong signal in both the amplitude and phase of α and that the modes behave quite differently from the background granulation signal. To get a better picture, Figure 2 shows the amplitude and phase as a function of frequency along the ridges. It is clear that both change dramatically as a function of frequency. This is, perhaps, not surprising since the frequency determines the near surface phase behavior of the modes (see Baldner & Schou 2012).

However, there is still significant scatter between the different radial orders, especially for the phase. Some of this is undoubtedly due to the varying oscillation/convection power ratio, which in itself makes the very low and high frequency results unreliable. Another thing to consider is that the oscillations are visible in both V and I. Indeed, studying V and I together provides information on the mode excitation and mode physics, as described in, e.g., Severino et al. (2008) and Severino et al. (2013). This also means that some of the effects seen may be due to the visibility of the modes in I, which is used to determine S. To correct for this, I' is low pass filtered with a cutoff of 2 mHz, to eliminate most of the mode signal and the analysis repeated. As Fig. 3 shows the scatter of the phase is indeed significantly reduced.

The amplitudes are quite interesting. The change with intensity is close to zero at the lowest reliable frequencies (i.e. ≈ 2.5 mHz) but becomes larger than unity above about 3.5 mHz, in other words a unit change in background intensity (corresponding, roughly to 100 km height change) causes of order unity change in the amplitude in the observed velocity.

It is also worth nothing that the phases are generally not close to 0 or 180 degrees. In other words the phases at different intensities are not generally in phase.

These results are, perhaps, not surprising given the results of Baldner & Schou (2012), who predicted large phase variations with height. A quantitative comparison is quite difficult, as Baldner & Schou (2012) did not address the same problem and since their final result depends on a delicate competition between positive and negative contributions from different heights and details of the radiative transfer. But noting that a unit change in the relative intensity corresponds to roughly 100 km height difference and assuming that there are no other effects, they saw phase changes of order tens of seconds (of order a radian), so it is not surprising that we observe changes of order unity.

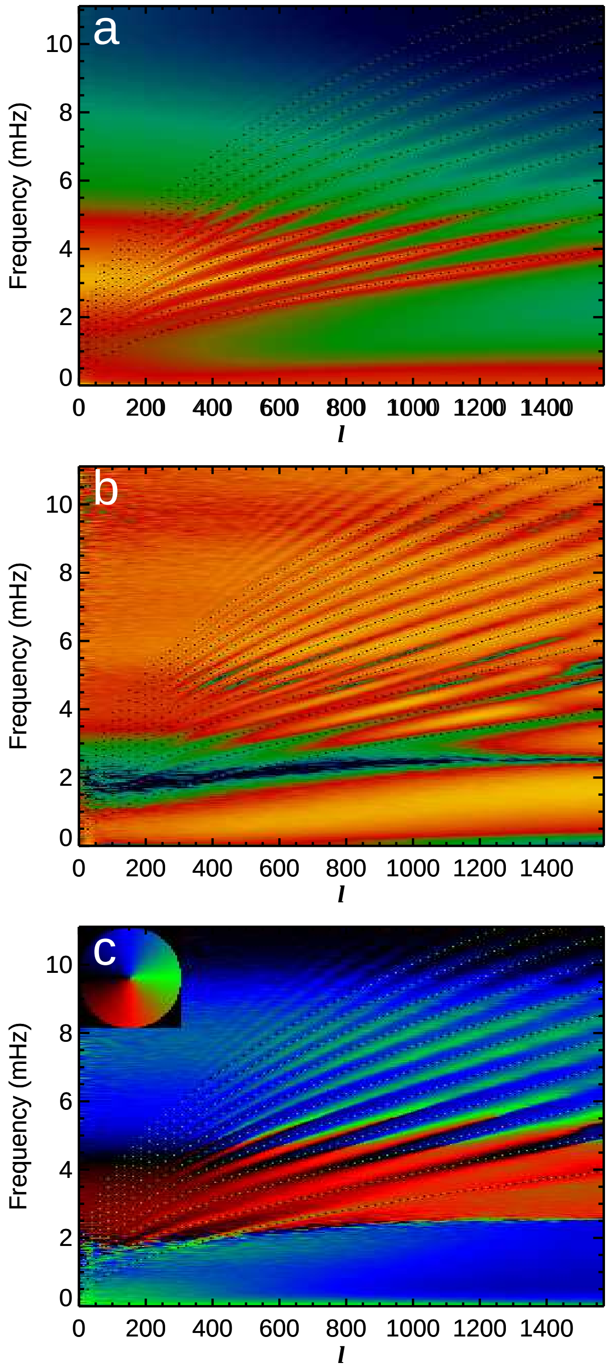

Fig. 1. From top to bottom, (a) shows the velocity power on a logarithmic scale with a range of 10^6 (blue-green-red-yellow), (b) the magnitude of α on a logarithmic scale from 0.1 to 10 and (c) the phase of α. The color coding for the phase is shown in the inset. Green (0°) corresponds to the amplitude increasing with I, black (180°) to decreasing, blue (90°) to the waves at higher intensity leading those at the reference intensity and red (270°) to trailing. Rough mode frequencies (courtesy of R. Bogart) for radial order $0 \leq n \leq 10$ are shown by dots.

[1] The averaging over ϕ and time is done by first interpolating each of the cross- and power-spectra to a grid in k and ϕ, averaging over ϕ and then averaging over time.

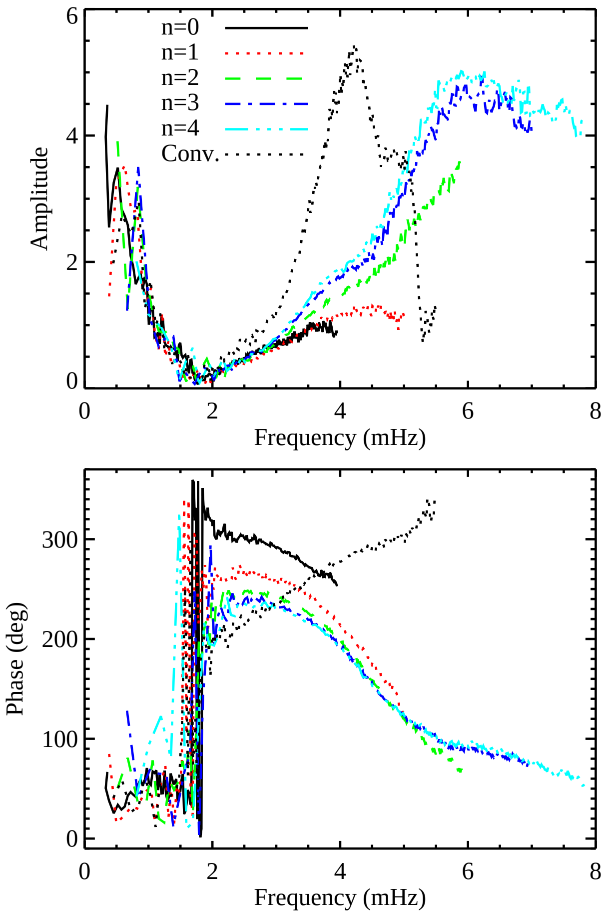

Fig. 2. Cuts through panels b and c of Fig. 1 along the ridges for n=0 through 4. Dotted black line shows the results for the noise evaluated half way between the $n = 1$ and $n = 2$ ridges. For the phase convention see the caption to Fig. 1. Note that the large oscillations in the phase just below 2 mHz are caused by the very low amplitude in that region and thus large noise sensitivity. This, in turn, also results in problems trying to unwrap the phase, which might otherwise have improved the presentation.

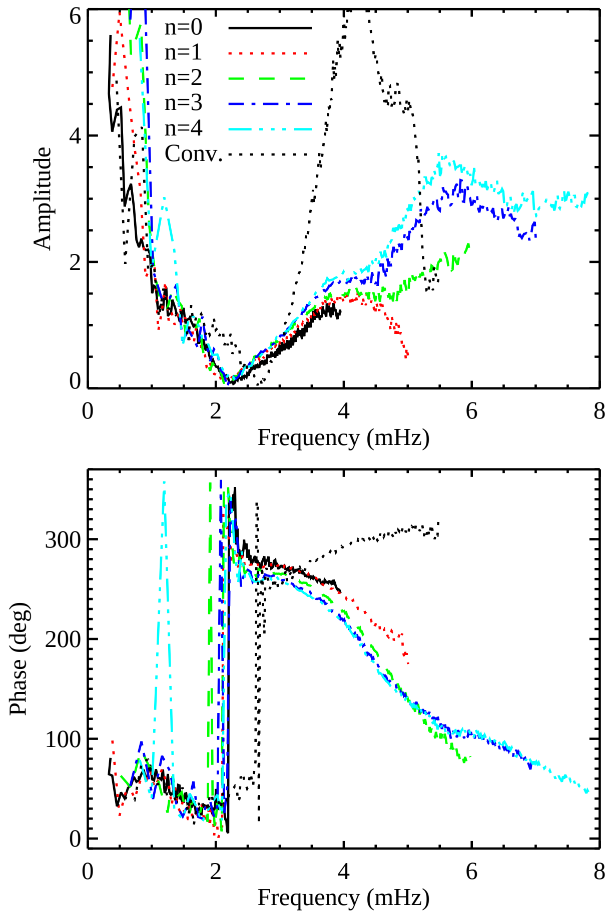

Fig. 3. As Fig. 2, but using intensities passed through a low pass filter with a cutoff frequency of 2 mHz.

However, more detailed predictions would require more detailed theoretical work. For attempts at this the reader is referred to Stix & Zhugzhda (2004) and references therein. Similarly, substantial insight might be obtained from numerical simulations.

As for the robustness of the results, it may be noted that using the low pass filtered Doppler velocity instead of the intensity leads to very similar results, except for a sign change (velocity and intensity are strongly anti-correlated in the granulation). Also, assuming that the variation is linear with intensity and that the velocity measurement process is linear, it follows that the slope is insensitive to blurring and thus to the instrument PSF.

As a likely cause of the phase shifts is the height dependence of the phase of the oscillations combined with the varying height of observation, one might expect some change with viewing angle, as that also changes the effective height of observation. As seen from Fig. 4 the phases are almost unaffected up to 40° from disk center. At 60° the results are dramatically changed, but are different for +60° and −60°, so this is likely not a robust result, most likely due to the substantial foreshortening. The amplitudes show more consistent changes. To what extent those changes are due to changes in the S/N has not been investigated.

One might also expect the intensity signal of the oscillation to change with position within the granulation pattern, which as Fig. 5 shows is indeed the case. Here the raw intensities were regressed with the filtered ones, in the same way as was done for the velocities. Given the lower S/N for intensity, these results are probably more affected by noise, but it is still clear that there is a strong signal and while the results for the modes and the background appear similar around 3 mHz, the S/N is actually quite significant there. It is interesting that the results are substantially more n dependent, probably reflecting differences in the mode physics (e.g. f modes do not compress the matter significantly, while p modes do). It is also interesting that the frequency dependence is different from that of the velocity, presumably reflecting the different heights of formation. It has not been investigated how other variables, such as line depth or width, vary.

Finally it may be noted that previous studies of waves over granules and intergranular lanes have been made (see, for example, Khomenko et al. (2001) and Kostyk et al. (2006) and references therein). Those studies were mostly concerned with attempts at detecting the excitation of modes or interactions with magnetic fields. Also, they did not investigate the dependence on k and ω and so were not able to resolve the modes clearly, which makes comparisons with the present work difficult.

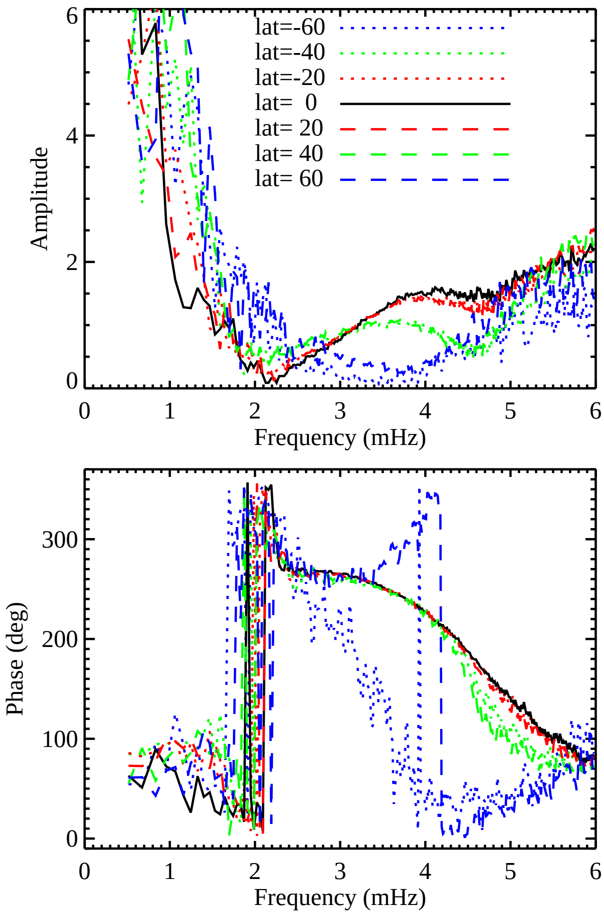

Fig. 4. Amplitudes and phase shifts for $n = 2$ at various latitudes. Note that the average B0 angle was only about 1°, so the viewing angle is effectively identical to the latitude.

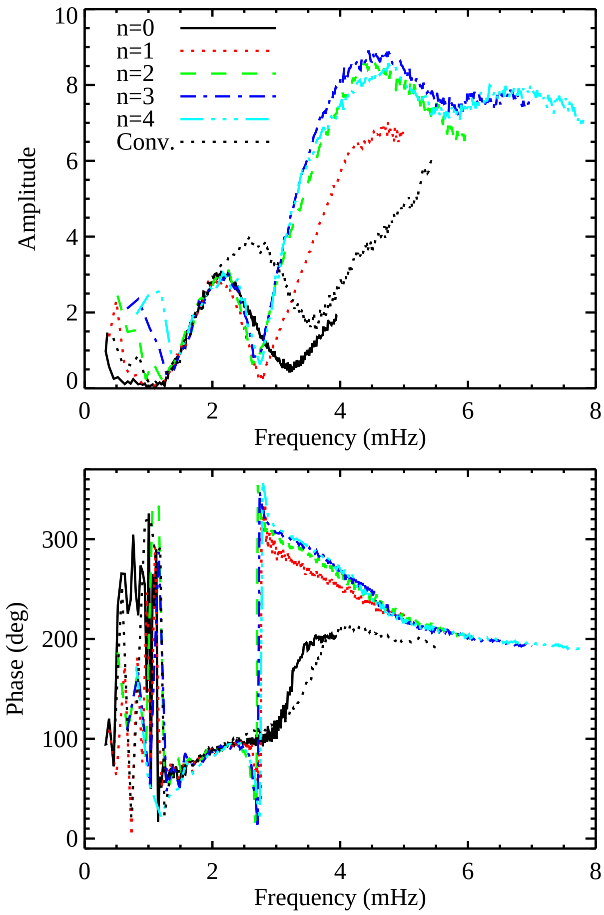

Fig. 5. As Fig. 3 but for the intensity.

4. Conclusion

Using the method described it is shown that the amplitudes and phases of the oscillations depend strongly on position in the granulation. Of course, this represents a correlation and does not imply that the intensity is the proximate cause. The velocity and intensity are highly correlated and no attempt was made to distinguish between their effects. No physical model of the effect has been made, but the large phase change with geometric height reported by Baldner & Schou (2012) combined with the change of observing height with intensity in the granulation is a promising candidate. Also, instrumental effects can not be completely excluded, especially for the amplitude effect, as there is some change in Doppler sensitivity with the thermodynamic properties where the line is formed.

A promising way to investigate the origin of the effects reported here is to analyze the results of large scale numerical simulations of near surface convection. Indeed, studies similar to those of Severino et al. (2013), but for the effects studied here, may prove very useful.

Observations with higher spatial resolution may also help shed more light on the relevant processes. In particular it may be possible to look for non-linearities and to disentangle the intensity and velocity effects. Similarly, higher spectral resolution may allow for the height dependence to be determined. It may also be possible to correlate against other variables, such as the magnetic field strength, alone or in combination with the intensity, thereby gaining further insight about e.g. magnetic field effects, a subject of significant current interest.

Note that, similar to the analysis by Nagashima et al. (2014), the analysis here only relies on existing HMI observations and does not require new observations using higher spatial resolution or other spectral lines. It is thus possible to study and exploit the effects described here using the existing 5 years of HMI data. An interesting possibility is that the effects described here may be exploited to further separate granulation from oscillations, thereby possibly leading to an improved S/N ratio.

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